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DYE IMAGE STABILITY OF POLAROID
TIME ZERO SUPERCOLOR PRINTS

by

Anthony Zych

B.S. United States Air Force Academy

(1977)

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in the Center for Imaging Science
in the
College of Graphic Arts and Photography
of the Rochester Institute of Technology

May, 1987

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CERTIFICATE OF APPROVAL

M. S. DEGREE THESIS

The M. S. Degree Thesis of Anthony Zych
has been examined and approved
by the thesis committee as satisfactory
for the thesis requirement for the
Master of Science degree

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Date

6-24-87

Model Automatic Focusing System for Linewidth
Measuring Instruments

by
John Ingraham

Submitted to the Imaging and Photographic Science Division in partial fulfillment of the requirements for a Bachelor of Science degree at Rochester Institute of Technology.

ABSTRACT

This paper discusses research on an automatic focusing system for IC-linewidth measuring instruments. The instrument incorporates a collimated light source, a device to move a sample in small, precise increments, and a charge-coupled device. The autofocus model would measure the step-height of a dielectric sample and correlate the height to a focus position. Thickness of samples on an enlarged scale were measured to verify the feasibility of this device.

ACKNOWLEDGEMENTS

Special thanks to Mr. Hadrian Lechner for time advising this research project, to Dr. Diana Nyyssonen from the National Bureau of Standards for linewidth theory, to Mr. Philip DePaula for electronics support to build the instrument, and to Mr. Jeff Pelz and Dr. Lynn Fuller for acquisition of samples. This research also would not be possible without the support and help from my parents.

TABLE OF CONTENTS

Section	Page
I. Introduction	1.
II. Experimental	13.
III. Data	22.
IV. Discussion	28.
V. Conclusion	29.
VI. References	31.
VII. Appendices	33.
VIII. Vita	41.

LIST OF TABLES

1. 40 Degree Reflection Angle Average Measurements,
Silicon Sample
2. 50 Degree Reflection Angle Average Measurements,
Silicon Sample
3. Calibration Chart for CCD
4. Micrometer Measurements
5. 40 Degree Reflection Angle Measurements, Silicon Sample
6. 50 Degree Reflection Angle Measurements, Silicon Sample
7. Glass Measurements

LIST OF FIGURES

1. P-N-P Junction Transistor
2. Intensity vs. Position Curve
3. Optical Profile for Incoherent and Coherent Illumination
4. Phase Angle and Reflectance Changes with Thickness Changes
5. Symmetric Line Object
6. Illustration of Optical Planes
7. Waveguide Object
8. Steepest Slope Measurement
9. Theoretical Apparatus
10. Actual System
11. Collimation of Light Source
12. Mount for Lens
13. Old Mounting for Original Instrument
14. Frame for CCD
15. Side View of Instrument
16. Rack System for Final Instrument
17. Glass Sample
18. Silicon Sample
19. Path Difference Measurement
20. Step Height Versus Reflection Angle
40 Degree Measurements
21. Step Height Versus Reflection Angle
50 Degree Measurements

I. INTRODUCTION

Obtaining accurate linewidth measurements on masks and wafers has been of important concern to the semiconductor industry. This is seen in the design of a p-n-p junction transistor (figure 1)¹.

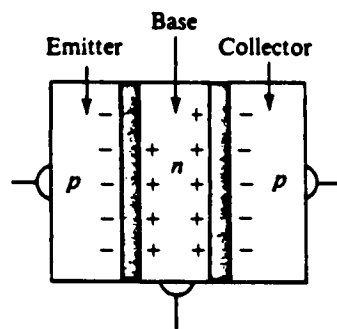


Figure 1.
p-n-p Junction Transistor

The device is composed of an emitter, base, and collector layers. The volume of each layer is crucial to the final performance of the device. Since the volume is the combination of the length, width, and height of an object, monitoring each of these parameters is important. This in turn prompted research in understanding linewidth characteristics.

There are many factors that affect the measurement of lines. Of these, the type of illumination and optics used, the reflectance and phase differences of the line with respect to the background, the shape of the line edges, material composition, and focus deviations appear to be major contributors in the final measurement. Similarly there has been a multitude of systems built to measure linewidth. One such system is the image scanning microscope.

When an object is measured by a image-scanning system, an optical profile is produced that is a measure of reflectance or transmittance versus position as seen in figure two. The correlation of the line edge to the image profile is called the optical threshold and varies with the type of illumination used² (figure 3). For incoherent sources, the threshold, T_c , is

$$T_c = .5(I_m + I_0), \quad (1)$$

while coherent illumination gives a threshold of

$$T_c = .25(I_m + I_0 + 2(I_m \times I_0)^{.5} \times \cos \theta)^{.3} \quad (2)$$

I_0 and I_m correspond to the reflectance (transmittance) of the background and the line respectively, and θ is the phase difference between the line and the substrate calculated by Fresnel equations.³

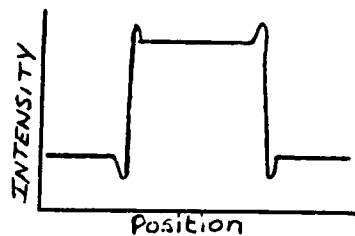


Figure Two.
Intensity refers to transmittance or reflectance

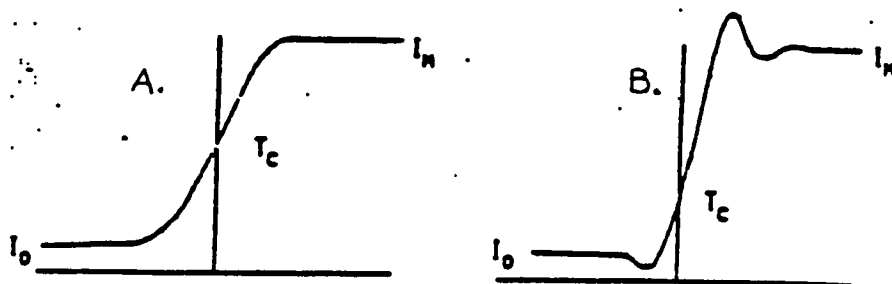


Figure Three.
A: Profile for Incoherent Illumination
B: Profile for Coherent Illumination
 T_c refers to the location of the object edge

Although incoherent illumination appears to be an easier method to determine linewidths, coherent light sources are used in most cases because incoherent illumination is not obtainable with conventional microscope lenses, and gives greater sensitivity with small changes in linewidth². In establishing coherent illumination, Kohler illumination³ is used to counteract variations in light wavetrains off axis and filament variations in the source. The collecting and illuminating optics are chosen to correspond with the proper coherence parameter, which is the ratio of the collecting and illuminating numerical apertures⁴. Monochromatic illumination is also used, preferably at a wavelength which gives minimum aberrations in the optical system⁵.

The characteristics of the material measured also affect the optical profile. A sample with vertical walls produces a different profile than a sloped sample. This in turn complicates the location of the threshold value. In metal samples, the refractive index of the material changes the optical profile by enhancing interference fringes at the image edge⁶. The overriding parameter affecting measurements appears to be film thickness. The thickness of silicon dioxide changes the reflectance and the phase angle compared to the silicon substrate⁴ as seen in figure four.

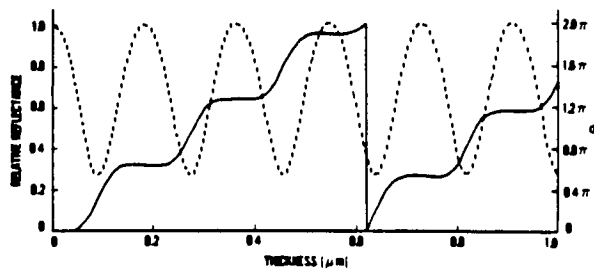


Figure Four
Phase Angle and Reflectance Changes with Thickness Changes

The thickness creates problems in establishing where to focus on the material and alters the Fourier components of the line object⁶. This has led to extensive research to model these problems⁶.

Thin-Layer Image Profile Model

In predicting the optical profile, changes in reflectance (transmittance), phase differences, and focus alterations are important parameters to the final profile calculation. Models were produced from work done by E. Kintner⁷ to simplify these profile computations. To use the model, a line object was created with a width W that repeats every interval P as seen in figure 5. The object is centered about the origin. The complex amplitude reflectance (transmittance) for the object is the following for a single period⁷:

$$\begin{aligned}
 A(x) &= 1 & 0 \leq |x| \leq W/2 \\
 &= T e^{i\theta} & W/2 \leq |x| \leq P/2.
 \end{aligned} \tag{3}$$

$$T = I_0/I_m$$

The Fourier series of the object is given by:

$$A(x) = \sum_m C_m B_m \cos(2\pi m x / P) \quad (4)$$

$$C_0 = .5(1 + Te^{i\theta}) \quad m=0$$

$$C_m = .5(1 - Te^{i\theta}) \quad m < 0$$

$$B_0 = 1 \quad m=0$$

$$B_m = 2\sin(\pi m W / P) / \pi m \quad m < 0$$

E. Kintner states that the Fourier transform of a slit, which scans $A(x)$, should also be incorporated in the model⁷. However, R. Kinzky found that it could be removed from the equation if the effective slit width is less than one sixth the Airy disk of the imaging lens⁸. Multiplying equation 4 by the pupil function $F(u)$ ⁶ given by

$$F(u) = \int_{-\infty}^{\infty} K(x) e^{-2\pi i u x} dx, \quad (5)$$

the coherent image equation is

$$I(y) = \left| \int_{-\infty}^{\infty} \left(\int_{-\infty}^{\infty} A(x) e^{-2\pi i u x} dx \right) F(u) e^{2\pi i y u} du \right|^2. \quad (6)$$

$K(x)$ is the complex amplitude impulse response of the imaging system⁵. The values of x, y and u correspond to one dimension of the object, imaging lens, and image planes respectively (Figure 6).

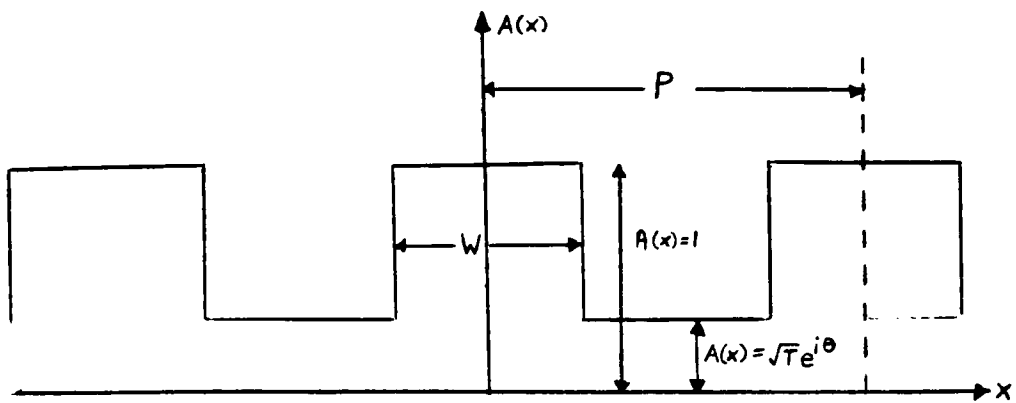


Figure Five.
Symmetric Line Object

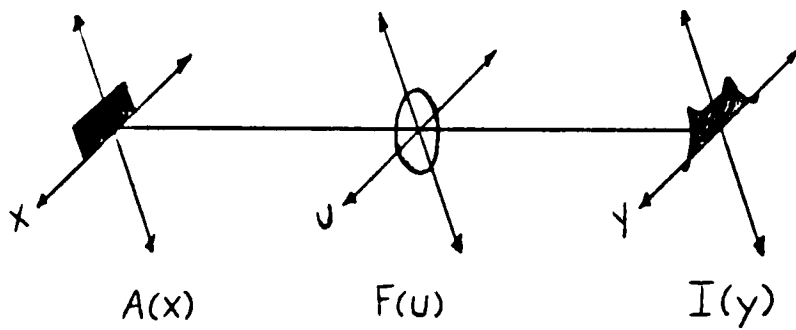


Figure Six.
 $A(X)$: Object Plane
 $F(u)$: Imaging Lens Plane
 $I(y)$: Image Plane

The model is complicated by the partial coherence effects in the illumination. The optical intensity for any state of coherence was found by E. Kintner⁶ to be

$$I(y) = \sum_n Z_n \cos(2\pi ny/P) \quad (7)$$

where Z contains the values of C and B in equation 4. This variable also incorporates the transmission cross coefficients³, which characterize the partial coherence of the illumination, and contain the pupil function in equation 5.

In equations 4 and 7, it is assumed that optimum focus has been established. To simulate defocus effects in the model optical profile, alterations are done on the pupil function stated in equation 5. This new pupil function is

$$F_d(u) = \exp(ikau^2) \text{ REC}(u, M/P) \quad (8)$$

where k is the wave number, a is the amount of defocus in wavelength units, and $\text{REC}(u, M/P)$ is a rectangular function of width M/P , which corresponds to the aperture diameter of the system⁶. With the above equations, the optical profile of a thin-layer material can be determined. However, most materials have step heights that are larger than the optical system's depth of focus. This in turn reflects the need for a thick-layer model to describe the optical profile.

Thick-Layer Model

In this model, a waveguide description⁹ of the object is created. The periodic function described in equation 4 is changed to the following:

$$\begin{aligned} e(x) &= n_0^2, & 0 \leq |x| \leq W/2 \\ &1, & W/2 \leq |x| \leq P/2, \end{aligned} \quad (9)$$

where e is the dielectric constant of the measured material, n_0 is the complex refractive index of the material, and one is the refractive index of air¹⁰.

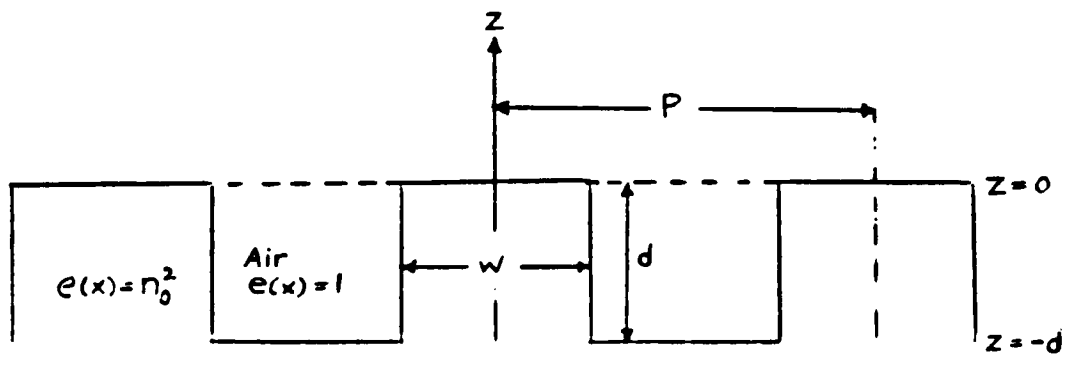


Figure Seven:
Waveguide Object

The symmetric object, as seen in figure seven, reduces equation nine to a series¹⁰ similar to equation 4:

$$e(x) = \sum_m e_m \cos(2\pi m x W/P). \quad (10)$$

The value e_m is equivalent to the product of B_m and C_m in equation 4 where

$$\begin{aligned} e_0 &= 1 + (n_0^2 - 1)W/P \\ e_m &= ((n_0^2 - 1)/(\pi m)) \sin(\pi m W/P) \quad m \neq 0. \end{aligned} \quad (11)$$

Since the source emits coherent light, the object is illuminated by a single plane wave normal to the material surface. The wave is then broken into its electric (E) and magnetic (H) field components in the form of tranverse magnetic modes¹¹. At certain boundary conditions¹⁰, the tangential components of these fields determine coefficients of the Fourier series:

$$E_R(x) = \sum_n a_n \cos(2\pi n x/P), \quad (12)$$

where $E_R(x)$ is the electric field reflected from the object, and a_n is similar to B_n and C_n . E_R , in fact, is a new object that can be analyzed by the thin-layer equations to produce a theoretical optical profile.

Even though the image profile can be modeled, proper focus is still needed to correlate this data to actual results. This concern has led to techniques to obtain correct focus. In conventional microdensitometer systems, a focusing system was developed to measure the intensity of the illumination before and

after going through a sample¹². When the incoming and outgoing intensities were at a fixed ratio, the sample was in focus. Commercial linewidth systems implement a variety of ways to obtain proper focus. One method is termed the steepest slope method. This technique measures the slope of the optical profile as seen in figure eight. The best focus is found when the slope of the line is a maximum. This method, however, has been proven inaccurate⁶.

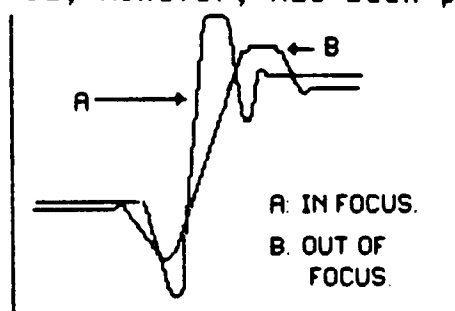


Figure Eight
Steepest Slope Measurement

Other systems measure by focusing on the top of the object. This technique ignores possible linewidth errors from defocus on the substrate. Rangefinder systems also are employed to properly focus on a wafer¹³, but this method is in a developmental stage. The errors induced by the above systems have demonstrated the need for a new system to maintain focus.

Interferometry has proven to be a useful tool for the measurement of samples. An interferometer system is currently used in the linewidth instruments at the National Bureau of Standards to measure the horizontal displacement of a sample⁵. However, many interferometer systems can also be used to measure the step height of a specimen. One system employs a Fizeau interferometer¹⁴ which is used to measure the topography of an optical surface. Another

instrument employs polarization interferometry in the measurement of thin films¹⁵. However, no commercial instrument employs interferometry in its linewidth system for the purpose of automatic focusing. One drawback with an interferometer is the added cost to conventional systems. Therefore, this paper covers construction of a step-height measuring system which, incorporated with an image scanning microscope, could automatically focus on a line. The step height is recorded for a line to be measured. Then the focus position is adjusted to correspond to a certain percentage of that height, which is viewed as the optimum focus.

STEP HEIGHT SYSTEM

The height-measuring system was constructed using a charge-coupled device (CCD)¹⁶. The CCD consists of a one dimensional array of photodiodes that are equally spaced. The output of each detector is stored in the form of a charge. This charge is then read by sending a clock pulse down the array. With each pulse, the charge is cascaded to an output device such as an oscilloscope. The oscilloscope can be observed to find the intensity at each element of the CCD. This CCD is implemented to measure a reflected beam hitting the sample.

In a simple case, a collimated light beam is produced which has a width less than the width of one element on the CCD. This collimated light bundle is positioned to hit the sample at a certain angle θ . The light is then reflected by the sample and falls incident on one element of the array. If the height changes, the light reflected hits another element a distance X

away. This can be seen in figure 9. This distance corresponds to a path difference in the light bundle. The path difference, in turn, is the key to measuring the step height since:

$$\text{STEP HEIGHT} = \text{PATH DIFFERENCE} \times \sin(\text{THETA}) \quad (13)$$

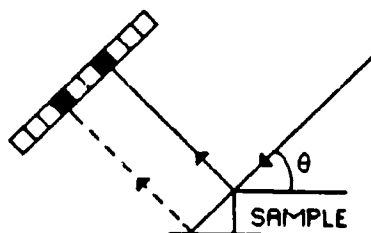


Figure 9.
Theoretical Apparatus

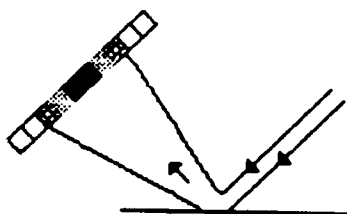


Figure 10.
Actual System

In actuality, the light bundle hits more than one element because of scatter from the reflected light and physical limitations in creating the light bundle as seen in figure 10. In this case, the intensity of light hitting the array is a maximum at the center of the reflected bundle. The path difference can then be calculated by observing the position change of the maximum. In this experiment, an apparatus is created to make step height measurements with a collimated light source and a CCD.

II. EXPERIMENTAL

In producing the step-height measuring instrument, many parameters were taken into account. These included the ability to create collimated illumination, power requirements for the charge-coupled device, brackets to hold the illumination and CCD array at the correct angle, and obtaining an instrument that could move a sample horizontally in small increments.

ORIGINAL INSTRUMENT

The collimated illumination was created in the following manner. The light source was a Rayovac disposable flashlight. This light was used for its square shape, which was conducive to easy mounting, and its adequate light output for the CCD to detect. A pinhole mask was placed in front of the flashlight to obtain a point source. The mask was made of sheet aluminum. To collimate the light, a reflecting flat was placed in front of the lens. This reflected the light back through the system. Proper collimation was obtained when the reflected beam fell back onto the pinhole (figure 11).

The power requirements for the CCD consisted of three power supplies with +5 volt, +15 volt, and -10 volt outputs. All supplies were connected to obtain a common ground. Then the voltages were adjusted with a rheostat built into each supply. The +5 volt supply also was used to power the light source.

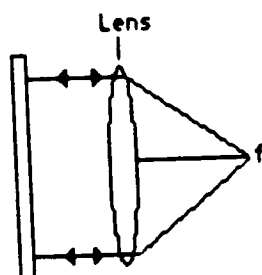


Figure 11.
 Light at the focus of the lens comes out parallel.
 Reflected beam which is parallel goes to focus.

Brackets were built to adjust the angle of the illumination hitting the sample, and to properly align the light source and the CCD. The brackets were machined from an aluminum bar 3/4 inch wide and 1/8 inch thick. The lens was mounted on a 3.5-inch sheet steel square in a manner similar to a lens board on a studio camera (figure 12). The square was then mounted with rivets onto an aluminum L-bar. The flashlight was placed on an aluminum bar. Set screws were provided to adjust the height of the pinhole to illuminate the center of the lens. Both the lens mount and the light assembly were then placed on another L-bar with slots to adjust the position of the lens. The bottom of the lens mount was also slotted for alignment purposes. Carriage bolts were used to fasten the lens and light setups on the aluminum bar. This can be seen in figure 13.

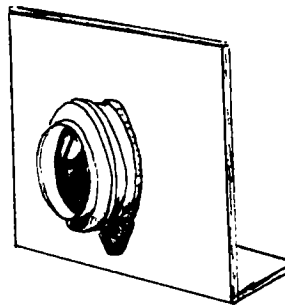


Figure 12.
Mount for Lens

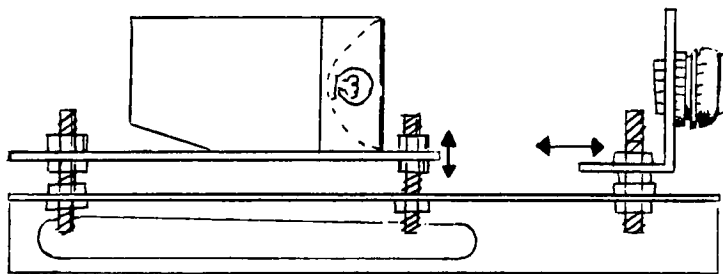


Figure 13.
Old Mounting Setup for Light-Lens System

To hold the CCD, a frame was designed to position the array vertically and horizontally. The CCD is a 3-inch square circuit board with 1/8-inch mount holes on each corner. The frame was designed with two slotted bars of aluminum and two threaded rods that are 8 inches long. The bars constituted the top and bottom parts of the frame while the rods were the sides. Sheet aluminum straps were made and put around the rods. An 1/8-inch hole was put in each strap where a nut and bolt can be placed to hold the CCD. On either side of each strap, a nut was placed to hold up the straps on the rod. The frame is shown in figure 14. The frame was then mounted on another L-bar of aluminum similar to the one holding the lens-light system. Both the frame and the lens-light system are mounted onto an L-bracket and aluminum bar assembly which attaches to the sample position instrument (figure 15).

The sample is moved with a Bausch and Lomb comparator. This instrument has a precision of .0005mm and adequate weight to prevent unwanted vibrations. Maintaining the sample at a constant horizontal position also was a requirement that the instrument facilitated. Mounting holes on either side of the instrument permitted the attachment of the lens-light and CCD brackets. Therefore, an instrument was developed with the above specifications.

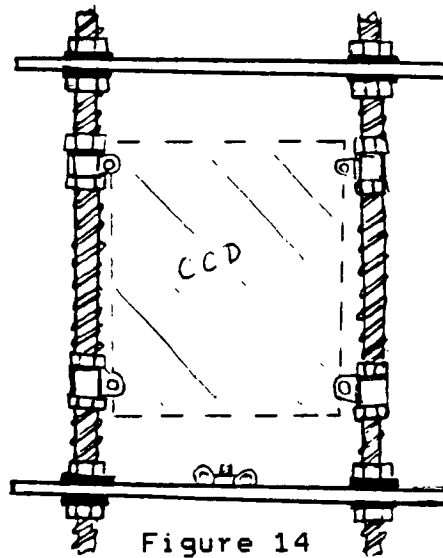


Figure 14
Frame for CCD

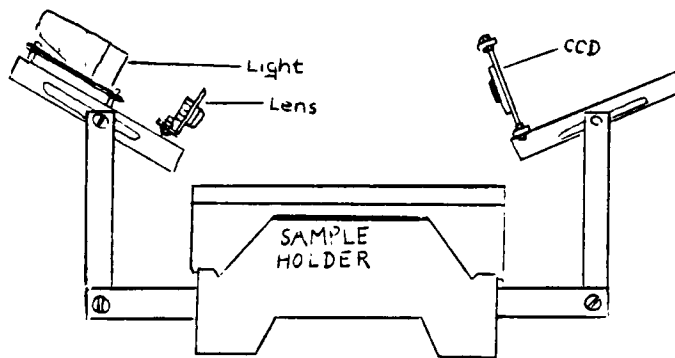


Figure 15.
Side View of Instrument

FINAL INSTRUMENT

After the original instrument was built, modifications were needed to create an operating system. The light source, which was originally powered by batteries, obtained power from a 5 volt power supply. This was done to eliminate alignment problems caused by removing the batteries. The flashlight reflector and pinhole mask were retained because they still were adequate for the system.

Changes in the brackets allowed for more precise movement of the light-lens system. The light, which was originally stationary, was placed on a rack to properly position the light with respect to the lens, as seen in figure 16. Vertical positioning of the light to the lens was accomplished by a set screw holding the lens. Instead of collimating the illumination, the pinhole was focused on the CCD array. This was done because of the inability to collimate a thin light bundle. The step height still could be measured since height altered the position of the pinhole image on the CCD array. Two protractors were also placed on the final instrument to measure the reflection angle of the light on the sample. With the final alterations, the instrument could proceed with sample measurements.

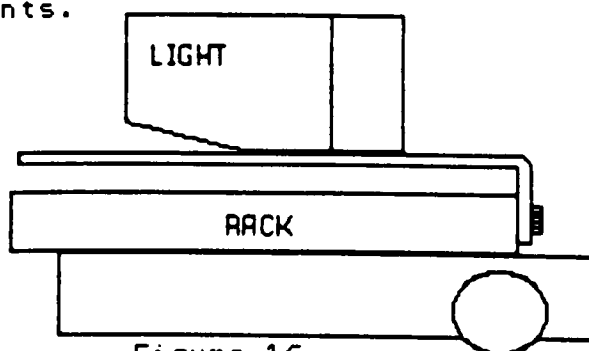


Figure 16.
Rack System

Measurements

Measurements with the instrument included calibration of the CCD array, reflection angle measurements, and step-height measurements. The CCD was connected to an oscilloscope to read the voltage values coming from each element of the CCD array. The oscilloscope was triggered by a clock pulse produced by the CCD. Since the charge-coupled device is an array of detectors, each element had to be calibrated to assure that the peak measurement was correct. This was done by measuring the difference in dark current response of each detector.

REFLECTION ANGLE MEASUREMENTS

Another measurement which had to be taken into consideration was the reflected light angle because the calculation of step height depended on this value. To test this, the following procedure was performed. A protractor was attached to the light-lens system and the angle the system made with the sample was recorded. The CCD array assembly, which also had a protractor attached to it, was adjusted to this same angle. Path difference measurements were then made at that angle, and at adjacent angles. This was performed to find the minimum path difference measurement. A minimum measurement would indicate that the reflected light was normal to the CCD array. The desired path difference measurement was then computed using the reflection angle to obtain the step height measurement.

SAMPLE MEASUREMENTS

Samples were then placed on the sample holder to measure the distribution of light reflected off a particular substrate. The substrates measured were glass, and silicon. Step height measurements were made of the glass by measuring the distance between the reflected beams off the top and bottom surface as seen in figure 17. The step height of the silicon wafer was measured by placing the silicon on a silicon substrate (figure 18). The thickness of the glass and the silicon wafer was then measured with a micrometer.

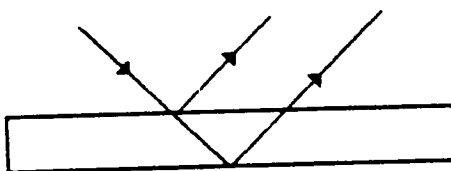


Figure 17.
Glass Sample



Figure 18.
Silicon on Silicon Sample

The path difference was determined by measuring the number of elements between the light distribution peaks (figure 19). This value was then multiplied by the distance between the elements,

which was 25 microns¹⁶, to obtain the actual path difference.

Measurements have been taken at reflected angles of 40 and 50 degrees with the silicon sample. Initial measurements were made at one-degree increments. This provided an approximate minimum. Then measurements were taken at half-degree increments to determine the more accurate minimum. For the 40-degree reflected angle, three sets of nine measurements were taken on the silicon sample. One set of nine measurements was taken with the 50-reflection angle. The glass sample was measured at the 40-degree angle minimum. The micrometer measurements were compared to the instrument values using hypothesis testing.

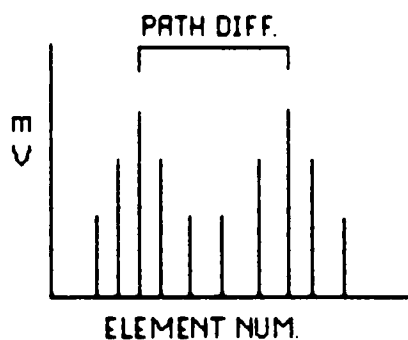


Figure 19.
Path Difference

III. DATA

A. CCD Calibration

Standard Deviation between array elements was 1.67 millivolts.

B. Micrometer Measurements

Ten measurements were done on the Si/SiO₂ sample and glass samples.

Si/SiO₂
Mean Thickness: .0210" (533.4 microns)
Standard Dev. : .0008" (20.00 microns)

Glass
Mean Thickness: .0485" (1245. microns)
Standard Dev. : .0006" (15.24 microns).

C. Instrument Measurements

1. 40 Degree Reflection Angle, Silicon Sample

Reflection Angle (degrees)	Delta* E (# of Elements)	Avg.** Delta E	Avg.@ Path Diff. (microns)	Step Height (microns)@
39.0	37.6 38.0 38.1	37.9	947.	596.
39.5	34.7 34.5 34.5	34.6	865.	550.
40.0	36.0 36.0 35.7	35.9	898.	577.
41.0	37.5 37.3 37.0	37.3	933.	612.

* Each value average of nine measurements

** Average of the twenty-seven measurements, standard deviation is \pm one element.

@ Standard Deviation is \pm 25.0 microns

2. 50 Degree Reflection Angle, Silicon Sample

Reflection Angle (degrees)	Delta* E (# of Elements)	Avg.@ Path Diff. (microns)	Step Height (microns)@
48.0	34.3	857.	637.
49.0	31.8	795.	599.
49.5	29.0	725.	551.
50.0	29.5	745.	570.
51.0	31.6	790.	613.

* Each value average of nine measurements

@ Standard Deviation is ± 25.0 microns

3. Glass Sample

Type: Crown

Index of Refraction: 1.517

Reflection Angle: 39.5 Degrees

Delta E: 37.6 elements

Path Difference : 940. microns

Step height: 1.25×10^3 microns

D. Hypothesis Test of Data

$$H_0 : \mu_1 - \mu_2 = 0$$

$$H_1 : \mu_1 - \mu_2 \neq 0$$

TEST IF POPULATIONS CAME
FROM SAME MEAN

$$t = A/(B+C)^{.5} \times (N_1(N_2)(N_1+N_2-2)/(N_1+N_2))^{.5}$$

$$A = \text{MEAN}_1 - \text{MEAN}_2$$

$$B = (N_1 - 1)S_1^2$$

$$C = (N_2 - 1)S_2^2$$

Degrees of Freedom: N_1+N_2-2

1. 40 DEGREE MEASUREMENTS

Micrometer Measurements:

MEAN₁ = 533.4 μm S_1 = 20.00 μm N_1 = 10

Instrument Measurements:

MEAN₂ = 550 μm S_2 = 25.0 μm N_2 = 27

t = 1.88 Degrees of Freedom: 35 or Infinite

$t_{.025}$ = 1.960 (Degrees of Freedom: Infinite)

Since $1.960 > t$, H_0 is not rejected for a 90 percent confidence interval.

2. 50 DEGREE MEASUREMENTS

MEAN₂ = 551. μm S_2 = 25.0 μm N_2 = 9

t = 1.56 Degrees of Freedom: 17

$t_{.025}$ = 2.093 (Degrees of Freedom: 17)

Since $2.093 > t$, H_0 is not rejected for a 90 percent confidence.

3. Glass Measurements

Micrometer Measurements:

MEAN1 = 1245 μm S1 = 15.24 μm N1 = 10

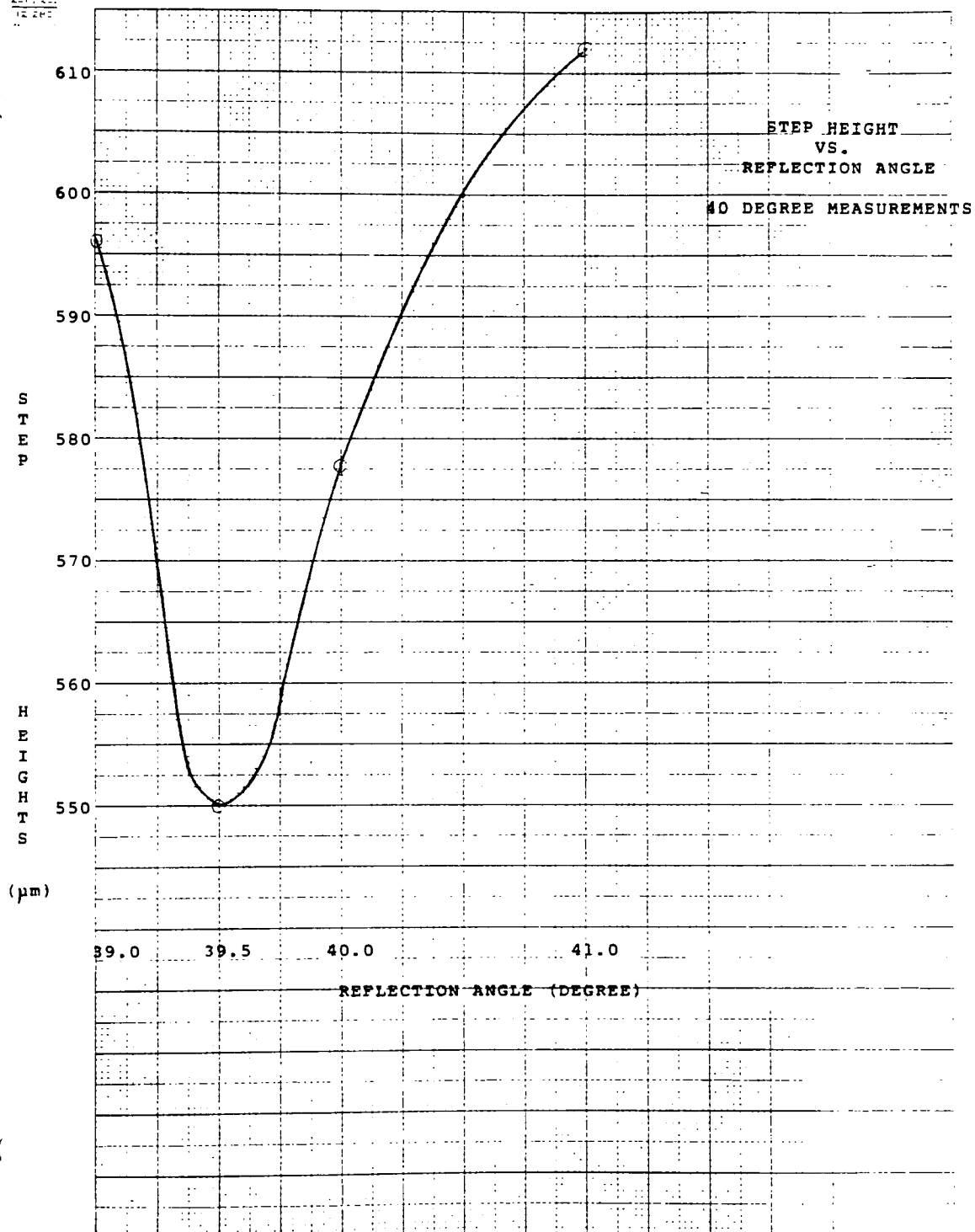
Instrument Measurements

MEAN1 = 1.25×10^3 μm S1 = 25.0 μm
N2 = 9

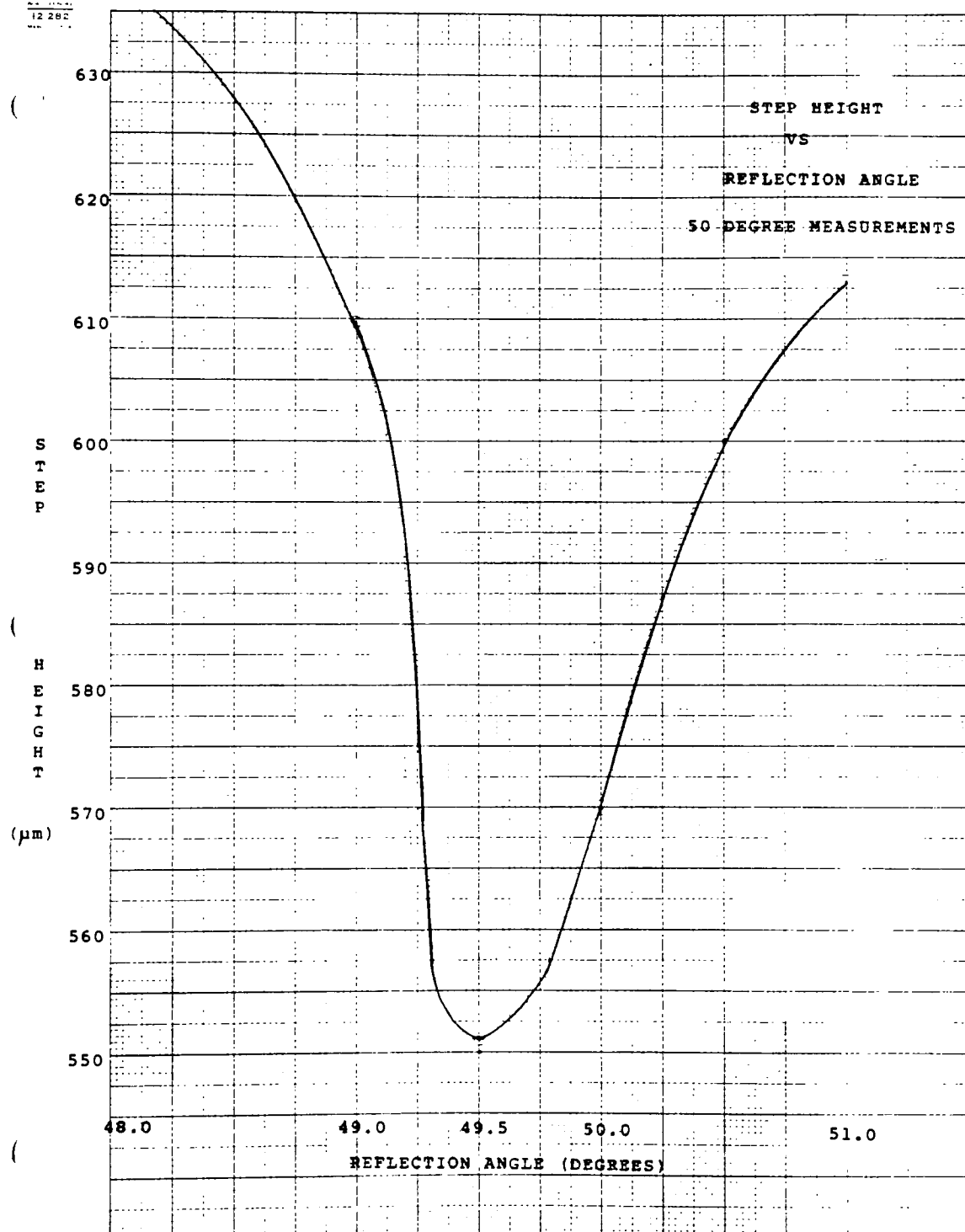
$\alpha = .05$ Degrees of Freedom: 17

$t_{.025} = 2.093$ (Degrees of Freedom: 17)

Since $2.093 > t$, H_0 is not rejected for a 90 percent confidence.



20 Squares to the Inch



20 Squares to the Inch

IV. DISCUSSION

From the data produced in this experiment, the step-height measuring instrument could measure the thickness of the tested samples. The calibration of the charge-coupled device gave a standard deviation of 1.67 mV between each detector. In the measurement of the silicon samples, similar results were found for the 40 degree and 50 degree reflection angle measurements. The 40 degree and 50 degree angles refer to the angle measured at the light-lens system. For both angles, the minimum angle measured at the CCD array assembly was .5 degrees less than the angle measured at the light-lens system. The step height at the 40 degree and 50 degree angles were 550 and 551 microns respectively. This verified that the measurement could be taken at more than one angle. The thickness versus angle plots showed that the step-height measurement dropped steeply to the minimum step-height value. This demonstrated that the reflected light could be placed normal to the charge-coupled device with an accuracy of one degree. Statistical analysis gave verification that the instrument measurements and micrometer thickness data could have come from the same population. For the silicon samples, hypothesis testing failed to be rejected with a 90 percent confidence. In evaluating the glass thickness data, the hypothesis test between the micrometer and instrument means also failed to be rejected for a 90 percent confidence. Therefore, the data demonstrated that the instrument could determine the step-height of the measured samples.

V. CONCLUSION

The results from this research represent one step towards the achievement of an automatic focusing system in linewidth measuring instruments. The instrument was able to obtain step-height values from the measured samples. These samples, although large in scale compared to actual material thicknesses, gave a good understanding of how the CCD would read the reflected light off glass, and silicon. For this system to function at actual scale, the instrument would need the following improvements.

CCD Array Improvements

The CCD array used would be too large for actual scale. The step height measurement is based on the angle of the reflected light bundle, and the distance between the CCD elements. For example, to measure a 5 micron sample with the CCD array in this experiment would require a reflection angle of:

$$A = \text{SIN}^{-1} (5 \text{ microns} / 50 \text{ microns}) = 5.7 \text{ degrees.}$$

This assumes that there are only two elements between the light-bundle peaks, and the sample is not a transparent medium. With a reflection angle of 5.7 degrees, the amount of light reflected off the sample would be reduced and scattered compared to a larger angle. By decreasing the distance between the CCD elements the angle could be increased. An alternative method would be to place two CCD arrays next to each other and shifted such that the void in one array could be read by the other array. The index

of refraction complicates the measurement limit of transparent materials, since this changes the reflection produced by the lower surface.

Light Source

The source would have to be changed to gain accurate readings on a smaller scale. The precise collimating of the light source was too difficult with the coarse adjustments on the instrument. An improved instrument would require either a way to collimate an incoherent light source, or a laser illuminating system. The laser system would require a rotating ground glass to remove speckle. Reducing the intensity of the light from the laser also would be required because the laser can destroy elements in the CCD.

Alignment and Vibration

The alignment of the CCD to the light source, proper positioning of the sample, and vibration factors are also needed improvements for a working system. The reflection angle could only be read to $\pm .5$ degrees with the designed instrument. A method to adjust the CCD with more precision and accuracy would facilitate easier alignment. Vibration could be decreased by isolation techniques such as using a vibration-free table.

Therefore, future work would be required to produce a instrument that would function at a working scale. Once an improved instrument could be developed, then the problems of adapting the system to a linewidth-measuring instrument would need further study as well.

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APPENDIX

A. SAMPLE CALCULATIONS

1. Hypothesis Test

MEAN1 = 533.4 um S1 = 20.00 um N1 = 10
MEAN2 = 550 um S2 = 25.0 um N2 = 27

$$H_0 : \mu_1 - \mu_2 = 0$$

$$H_1 : \mu_1 - \mu_2 \neq 0$$

TEST IF POPULATIONS CAME
FROM SAME MEAN

$$t = A/(B+C)^{.5} \times (N1(N2)(N1+N2-2)/(N1+N2))^{.5}$$

$$A = \text{MEAN1} - \text{MEAN2}$$

$$B = (N1 - 1)S1^2$$

$$C = (N2 - 1)S2^2$$

Degrees of Freedom: $N1+N2-2$

$$A = 550 - 533.4 = 16.6$$

$$B = (9)(400) = 3.60 \times 10^3$$

$$C = (26)(625) = 1.63 \times 10^4$$

$$(N1(N2)(N1+N2-2)/(N1+N2))^{.5} =$$

$$(270(35)/(37))^{.5} = 16.0$$

$$t = 16.6(16.0)/(3.60 \times 10^3 + 1.63 \times 10^4)^{.5} \\ = 1.88$$

Degrees of Freedom = $N1+N2-2 = 35 = \text{Infinite}$

$$t_{.025} \text{ (Two Tail Test)} = 1.96 \text{ (DOF=Infinite)}$$

Since $t_{.025} > t$, H_0 fails to be rejected.

$t = 1.88$ Degrees of Freedom: 35 or Infinite

$$t_{.025} = 1.96 \text{ (Degrees of Freedom: Infinite)}$$

Since $1.96 > t$, H_0 is not rejected for a 90 percent confidence interval.

2. Glass Thickness Calculation

$$N = 1.517$$

$$\text{Num. of Array Elements between Peaks} = 37.6$$

$$\text{Reflection Angle} = 39.5 \text{ Degrees}$$

Using Snell's Law:

$$\sin(A2) = \sin(A1)/N \quad (\text{in air})$$

$$A1 = 90.0 - 39.5 = 50.5 \text{ degrees}$$

$$\sin(A2) = .772/1.517 = .509$$

$$A2 = 30.6 \text{ degrees}$$

$$\text{Path Difference} = PD = 37.6(25) = 940 \text{ microns}$$

$$\cos(A1) = PD/(2X)$$

$$\tan(A2) = X/T$$

$$PD = (2X)\cos(A1)$$

Substituting for X,

$$PD = (2T)\tan(A2)\cos(A1)$$

$$\text{or} \quad T = PD/(2\tan(A2)\cos(A1))$$

For the Example,

$$T = 940/(2\tan(30.6)\cos(50.5))$$

$$T = 1.25 \times 10^3 \text{ microns.}$$

B. EQUIPMENT

Lens Used: Wollensak 1 inch f/1.9 movie lens
Number: 856699

CCD Used: EGG Reticon Type 301
Number: 930-0038/11344-147
128 Element Array

Bausch and Lomb Width Measuring Device
Number: 30015

Power Supplies:
Technipower: 15V 5V
Number: S16691 S16681

Micronta: 0-25V (0-1.25 Amps)
Number: 22-123

Oscilloscope:
Tektronics Type 7613
Number: 81206703

Micrometer:
Precision Instruments
Number: 8011567

Protractors:
C-Thru Ruler Company
Number: 376

C. TABLE 3.
CALIBRATION CHART FOR CCD

The first element in the array is positioned as zero on the oscilloscope. Output is in millivolts.

Element Number	mV	Element Number	mV	Element Number	mV
1	0	35	20	69	20
2	10	36	20	70	21
3	30	37	20	71	20
4	30	38	19	72	20
5	20	39	20	73	20
6	20	40	20	74	20
7	21	41	20	75	20
8	19	42	20	76	20
9	20	43	20	77	20
10	21	44	20	78	21
11	21	45	19	79	49
12	21	46	20	80	49
13	21	47	20		
14	21	48	20		
15	21	49	20		
16	21	50	20	Mean: 20.39 millivolts	
17	20	51	20	Standard Deviation: 1.67	
18	21	52	20	millivolts	
19	21	53	20		
20	21	54	20		
21	21	55	20		
22	21	56	20		
23	20	57	21		
24	21	58	19		
25	20	59	20		
26	20	60	21		
27	20	61	21		
28	21	62	20		
29	21	63	20		
30	19	64	20		
31	20	65	21		
32	20	66	50		
33	20	67	19		
34	20	68	19		

Only 80 elements of the Detector were used in the experiment. The mean does not take into account elements 1-4 because these elements also were not used in measurements.

D. TABLE 4.
MICROMETER MEASUREMENTS

	Silicon (inches)	Crown Glass (inches)
	.0210	.0485
	.0210	.0485
	.0209	.0478
	.0210	.0480
	.0209	.0485
	.0212	.0490
	.0210	.0485
	.0210	.0480
	.0210	.0494
	.0209	.0490
MEAN	.0210	.0485
STD.	.0008	.0006
DEV.		

E. INSTRUMENT MEASUREMENTS

TABLE FIVE

40 DEGREE STEP HEIGHT MEASUREMENTS

ANGLE (DEGREES)	AVG.* POSITION ONE (# of ELEMENTS)	AVG.* POSITION TWD (# of ELEMENTS)	DELTA ELEMENTS (ELEMENTS)	PATH DIFFERENCE (MICRONS)	STEP HEIGHT (MICRONS)	AVG.** STEP HEIGHT (MICRONS)
39.0	58.5	20.5	38.0	950	598	596
39.0	55.3	17.5	37.8	945	595	
39.0	57.2	20.0	37.2	930	585	
39.0	71.8	34.0	37.8	945	595	
39.0	70.2	32.0	38.2	955	601	
39.0	70.2	32.0	38.2	955	601	
39.0	58.0	19.5	38.5	963	606	
39.0	57.5	20.0	37.5	938	590	
39.0	58.0	19.5	38.5	963	606	
39.5	45.0	10.3	34.7	868	552	550
39.5	47.0	12.3	34.7	868	552	
39.5	49.0	14.3	34.7	868	552	
39.5	72.0	37.5	34.5	863	549	
39.5	71.0	36.7	34.3	858	545	
39.5	72.0	37.5	34.5	863	549	
39.5	60.0	25.2	34.8	870	553	
39.5	63.0	28.0	35.0	875	557	
39.5	61.7	27.0	34.7	868	552	
40.0	57.2	21.2	36.0	900	579	577
40.0	59.3	23.3	36.0	900	579	
40.0	62.3	26.3	36.0	900	579	
40.0	57.3	21.3	36.0	900	579	
40.0	57.3	21.3	36.0	900	579	
40.0	57.3	21.3	36.0	900	579	
40.0	67.0	31.3	35.7	893	574	
40.0	66.0	30.3	35.7	893	574	
40.0	68.0	32.3	35.7	893	574	
41.0	59.0	21.5	37.5	938	615	612
41.0	57.0	19.5	37.5	938	615	
41.0	60.5	23.0	37.5	938	615	
41.0	63.2	26.0	37.2	930	610	
41.0	66.5	29.0	37.5	938	615	
41.0	70.2	33.0	37.2	930	610	
41.0	55.5	18.5	37.0	925	607	
41.0	55.5	18.5	37.0	925	607	
41.0	56.0	19.0	37.0	925	607	

* AVG. OF THREE MEASUREMENTS

** AVG. OF TWENTY-SEVEN MEASUREMENTS

TABLE SIX.

50 DEGREE STEP HEIGHT MEASUREMENTS						
ANGLE (DEGREES)	AVG.* POSITION ONE (# of ELEMENTS)	AVG.* POSITION TWO (# of ELEMENTS)	DELTA ELEMENTS (ELEMENTS)	PATH DIFFERENCE (MICRONS)	STEP HEIGHT (MICRONS)	AVG.** STEP HEIGHT (MICRONS)
48.0	46.3	12.0	34.3	858	637	637
48.0	47.3	13.0	34.3	858	637	
48.0	46.3	12.0	34.3	858	637	
49.0	52.8	21.0	31.8	795	600	599
49.0	46.8	15.0	31.8	795	600	
49.0	48.8	17.0	31.8	795	600	
49.5	50.0	21.0	29.0	725	551	551
49.5	48.0	19.0	29.0	725	551	
49.5	46.3	17.3	29.0	725	551	
50.0	73.3	43.0	30.3	758	580	570
50.0	73.5	44.0	29.5	738	565	
50.0	75.8	46.0	29.8	745	571	
51.0	43.3	11.5	31.8	795	618	613
51.0	45.2	14.0	31.2	780	606	
51.0	44.3	13.0	31.3	783	608	

TABLE SEVEN.

GLASS MEASUREMENTS						
ANGLE (DEGREES)	AVG.* POSITION ONE (# of ELEMENTS)	AVG.* POSITION TWO (# of ELEMENTS)	DELTA ELEMENTS (ELEMENTS)	DELTA ELEMENTS (ELEMENTS)	PATH DIFFERENCE (MICRONS)	AVG.** STEP HEIGHT (MICRONS)
39.5	59.0	21.2	37.8	37.6	940	1.25E+03
39.5	58.7	21.2	37.5			
39.5	57.7	20.3	37.4			

* AVG. OF THREE MEASUREMENTS

** AVG. OF NINE MEASUREMENTS

TABLE SIX.

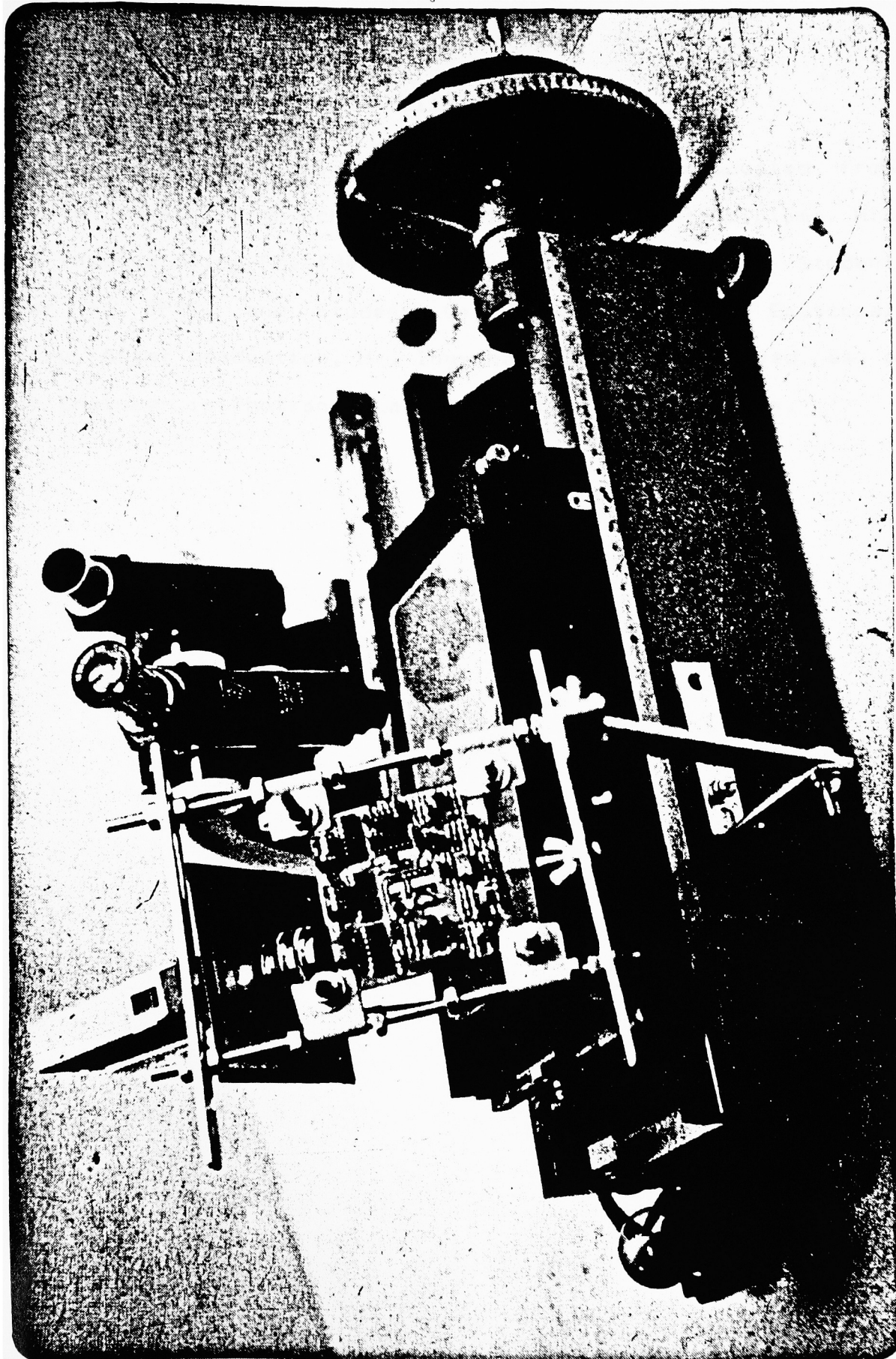
50 DEGREE STEP HEIGHT MEASUREMENTS						
ANGLE (DEGREES)	AVG.* POSITION ONE (# of ELEMENTS)	AVG.* POSITION TWO (# of ELEMENTS)	DELTA ELEMENTS (ELEMENTS)	PATH DIFFERENCE (MICRONS)	STEP HEIGHT (MICRONS)	AVG.** STEP HEIGHT (MICRONS)
48.0	46.3	12.0	34.3	858	637	637
48.0	47.3	13.0	34.3	858	637	
48.0	46.3	12.0	34.3	858	637	
49.0	52.8	21.0	31.8	795	600	599
49.0	46.8	15.0	31.8	795	600	
49.0	48.8	17.0	31.8	795	600	
49.5	50.0	21.0	29.0	725	551	551
49.5	48.0	19.0	29.0	725	551	
49.5	46.3	17.3	29.0	725	551	
50.0	73.3	43.0	30.3	758	580	570
50.0	73.5	44.0	29.5	738	565	
50.0	75.8	46.0	29.8	745	571	
51.0	43.3	11.5	31.8	795	618	613
51.0	45.2	14.0	31.2	780	606	
51.0	44.3	13.0	31.3	783	608	

TABLE SEVEN.

GLASS MEASUREMENTS						
ANGLE (DEGREES)	AVG.* POSITION ONE (# of ELEMENTS)	AVG.* POSITION TWO (# of ELEMENTS)	DELTA ELEMENTS (ELEMENTS)	DELTA ELEMENTS (ELEMENTS)	PATH DIFFERENCE (MICRONS)	AVG.** STEP HEIGHT (MICRONS)
39.5	59.0	21.2	37.8	37.6	940	1.25E+03
39.5	58.7	21.2	37.5			
39.5	57.7	20.3	37.4			

* AVG. OF THREE MEASUREMENTS

** AVG. OF NINE MEASUREMENTS



Photograph of Instrument
(Power Supplies and Oscilloscope not shown)

VITA

John Ingraham, a native of Cazenovia, NY, graduated from Cazenovia Central High School in 1981 with a Regents diploma. His honors include being President and Treasurer of the RIT Student Chapter of SPSE, and Student Coordinator of the RIT Episcopal Ministry. After graduation, Mr. Ingraham will be employed as a Junior Engineer in Photronic Labs located in Danbury, Conn.